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Precision Pointing for the Pluto Mission Spacecraft

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PRECISION POINTING FOR THE PLUTO MISSION SPACECRAFT

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The elements of an attitude control subsystem to support precision pointing for the Pluto mission and spacecraft are described. Cost, mass, schedule and performance, approximately in that order, drove the mission, spacecraft as well as the attitude control subsystem design. The spacecraft is a three axis stabilized vehicle using cold gas jets for attitude control and hydrazine thrusters for trajectory correction maneuvers. The inertial reference unit will be used for attitude determination during trajectory collection maneuvers. The star tracker is the key hardware assembly supporting attitude determination for precision pointing during the Pluto/Charon encounter. Both the star tracker and inertial reference unit are described in the paper. An attitude determination and control scheme to support precision imaging at Pluto encounter is sketched.

INTRODUCTION

The key elements in support of precision pointing for a mission to Pluto are described. The design is a result of a continuing mission development activity at Jet Propulsion Laboratory on a small spacecraft (180 kg) for a mission to Pluto, the one planet in the solar system yet to be explored by robotic spacecraft. Two spacecraft, each with internal hardware redundancy, are to complete fast flybys of Pluto and its moon Charon following direct trajectories from Earth. The science instruments include visible and infrared imagers (visible imaging is intended to provide 1 km global resolution), an ultraviolet spectrometer, a radio science experiment to be used during Earth occultations by Pluto's atmosphere and finally a drop probe provided by the Russians to measure constituents in Pluto's atmosphere. The mission for each spacecraft is expected to last 10 years. Described in this paper will be the fiscal year (FY) 1994 baseline which at the time was called the Pluto Fast Flyby spacecraft.

In the next sections we provide a description of the Pluto-Charon system followed by a brief discussion of past Pluto studies. The mission scenario and spacecraft design are briefly reviewed. The attitude control requirements and subsystem are then presented. Attention is then given to the inertial reference unit and star tracker hardware supporting the attitude determination and precision pointing, function of the spacecraft. Issues to consider for an open loop pointing scheme at Pluto encounter are discussed. Concluding remarks are made in the final section.

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THE PLUTO-CHARON SYSTEM

Pluto is normally the planet farthest from the Sun during its 248 year orbit, but since 1979 it has been inside the orbit of Neptune, reaching perihelion in 1989. By 1999 it will once again be the outermost planet. For several years around perihelion Pluto has a tenuous atmosphere, which will eventually collapse as it moves outside the orbit of Neptune. By 2020 it is expected that Pluto's atmosphere will have largely condensed. Because of the temporary nature of its atmosphere and the fact that Pluto has yet to be explored, a flyby mission to Pluto appears attractive.

Pluto is somewhat smaller than the Earth's moon (the radius of Pluto is 1150 km compared with the moon's radius of 1740 km) and itself has a moon Charon about half of the diameter of Pluto. From Earth based observations [1], it appears that Pluto can best be modeled by Neptune's moon Triton, while Charon most closely resembles the Uranian moon Ariel. The semimajor axis of Charon's orbit is 19640 km and Charon orbits Pluto every 6.4 days, the same as Pluto's rotation period

Pluto is believed to be 70% rock and approximately 30% watt.r ice with a thin methane ice surface. Its color is expected tobe pinker than Triton, but not as red as Mars. Pluto also has dark mare-siml surface markings. Charon apparently only has a water ice surface.

SOME PAST PLUTO MISSION STUDIES

Several missions have been proposed to Pluto in the past. The original scenarios for a Grand Tour[2] of the outer planets called for a flyby of Pluto, and more recently, studies at Jell'roI~L]lsiolll .:ll]()]:lt()]j'il] 1990 and 1992 examined flyby missions lasting 14 years with a 500" kg spacecraft. The present mission development phase began in 1992, with an original design goal of two 35 kg spacecraft.

Most of the spacecraft proposal for Pluto flybys have been three axis stabilized[3]; however, a modification 10 the spinning Pioneer spacecraft had been proposed for a Grand Tour which included a flyby of Pluto[4].

MISSION SCENAR1O AND CONSTRAINTS

Cost, mass, schedule and performance, approximately in that order, have drive.n the mission, spacecraft, as well as the attitude control subsystem design. Details on the FY 94 mission scenario can be found in Refs. 5-7.

The FY 94 baseline calls for two spacecraft to complete 9.3 year and 9.8 year direct trajectories to Pluto with flybys at a relative speed to the planet of approximately 15 km/sec. See Figure 1. During approach, both sides of Pluto will be imaged; however, the detailed mosaic done about an hour and a half prior to closest approach will only be of one side, while detailed images of the other side will be made during the flyby of the second spacecraft.

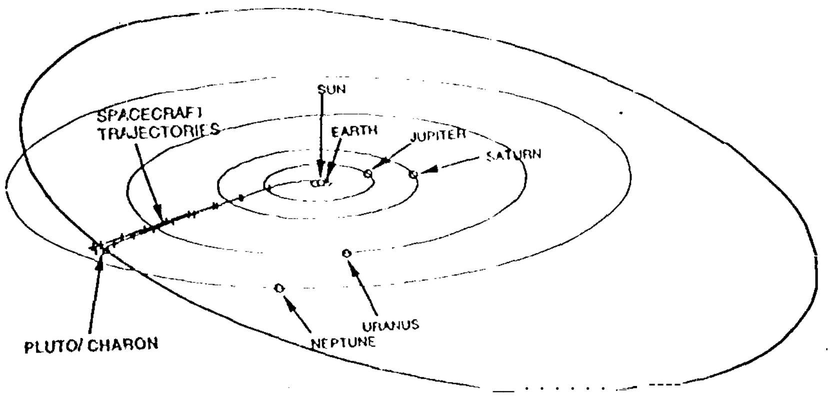

Figure 1 Direct Trajectories to Pluto

The change in velocity required to be executed by the spacecraft during the cruise phase of the mission is expected to be 360 m/sec. Most of the change in velocity budget will be used to correct for errors in the interplanetary injection made by the two spin stabilized solid rocket motors sitting on top of the Proton booster. Otherwise the cruise period will be relatively uneventful with minimal spacecraft to Earth communications.

The Russian drop probe will be ejected 32 days prior to encounter. The near encounter period with Pluto and Charon will last only a few hours during which most of the imaging will be done, data will be relayed from the drop probe and the occultation experiments will be executed. The maximum image motion compensation rate will be 1 mrad/sec. One way light time at Pluto encounter will be about four hours.

THE SPACECRAFT

A diagram of the FY 94 baseline Pluto spacecraft is shown in Figure 2. The spacecraft is three axis controlled using cold gas thrusters without reaction wheels or a scan platform. The wet mass of the spacecraft is 182 kg, while the dry mass stands at 158 kg. At encounter 78 watts is expected to be available from the radioisotope thermoelectric generator. Moments of inertia at encounter will range from about 15 kg-m^2 for the y axis to 30 kg-m^2 for the other two axes. The spacecraft components will be designed to withstand radiation with a total ionizing dose of 22 kRad (Si) over a 10 year mission.

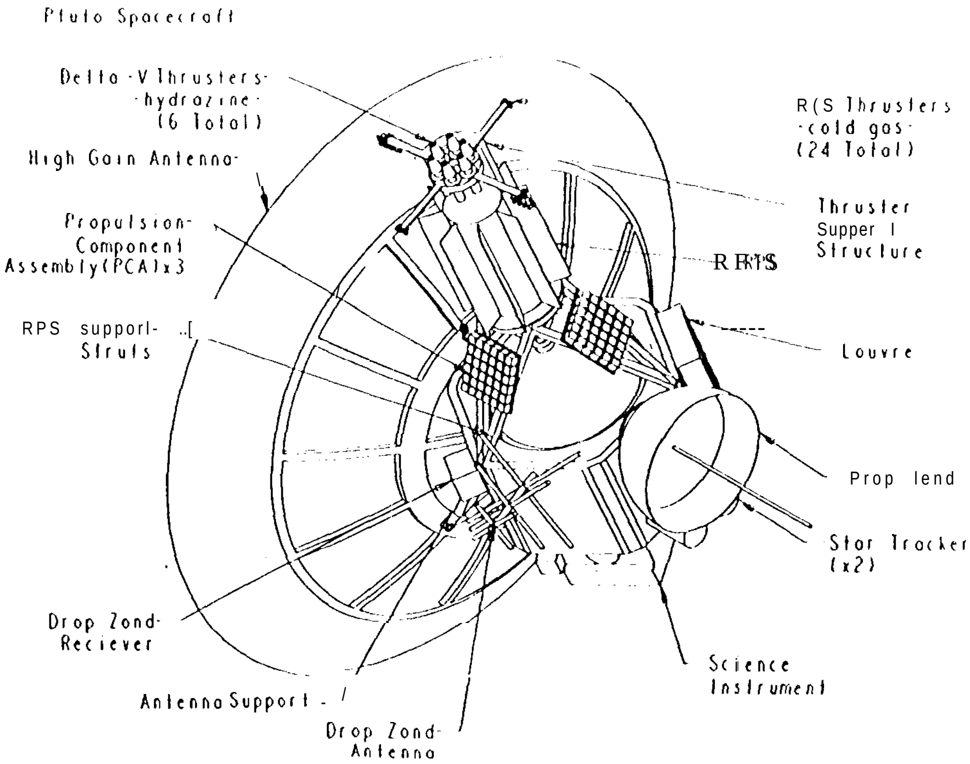

Figure 2 The Pluto Mission Spacecraft, FY 94 Baseline

As the Pluto mission development activity progresses, changes to the mission scenario may require important modifications to the spacecraft. For example, the possibility of a trajectory using Jupiter for a gravity assist would require enhanced shielding for electronic components on the spacecraft.

ATTITUDE CONTROL SUBSYSTEM REQUIREMENTS AND DESIGN

Different operational modes of the Pluto spacecraft define different attitude control requirements. The only mode in which precision pointing is required is the imaging mode during the Pluto flyby. In addition to the imaging mode we will discuss the trajectory correction maneuver mode which makes use of the inertial reference unit. All requirements will be 3σ values unless stated otherwise. A block diagram of the attitude control subsystem is shown in Figure 3.

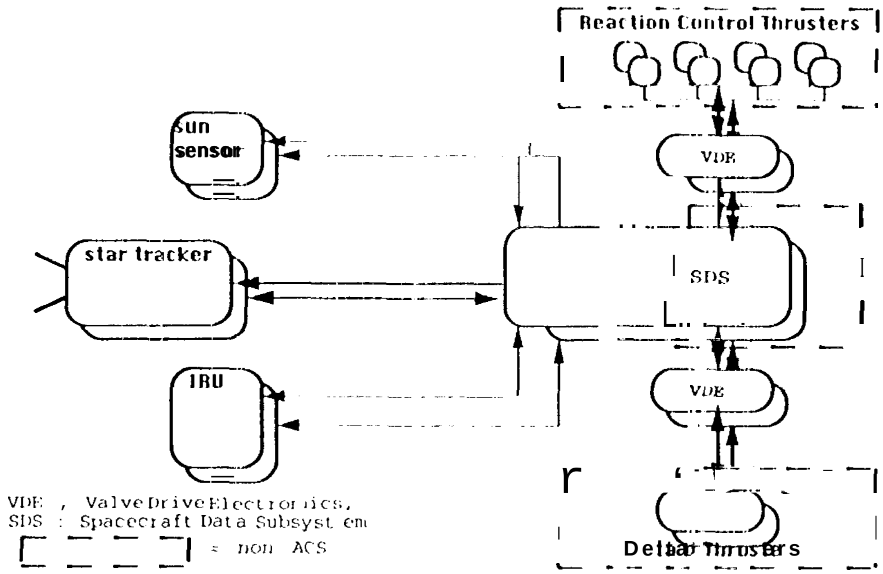

Figure 3 Attitude Control Subsystem Block Diagram

The trajectory correction maneuvers are executed by three of six 4.45 N hydrazine thrusters used in an off-pulse mode for thrust vector control. Additional 0.15 N cold gas thrusters will provide roll control during the. trajectory correction maneuvers. The trajectory correction maneuvers require that the net pointing error be no greater than 36 mrad.

The most critical pointing requirements will of course occur during the fast flybys of Pluto and Charon. The pointing capability is expected to match or better that of Voyager 2 during its encounter with Neptune. The requirement for pointing knowledge is 1.5 mrad and the pointing control requirement is 2.0 mrad. Keeping the rate of the spacecraft within 10 µrad/sec of the desired image motion compensation rate is the most stringent pointing requirement for the entire mission. The maximum image motion compensation rate is expected to be 1 mrad/sec.

Cold gas (gaseous N_2) thrusters have been developed for this mission with a small enough impulse bit to meet the rate control requirement of 10 µrad/sec with a 0.2.5 m thruster moment arm. These thrusters have a 0.005 N thrust and could have minimum on times on the order of 4 - 5 msec. Sixteen cold gas thruster provide reaction control for most modes of the mission. Note that the Voyager spacecraft also had a scan platform that was used for image mosaicking; however, the most successful image motion compensation was done with the thrusters and not its scan platform.

ATTITUDE DETERMINATION

Because of the severe mass constraints for the Pluto mission, it was imperative to have as low a mass possible for attitude determination hardware. Therefore, it was obvious that an inertial reference unit like the Fiber Optic Rotation System proposed by a previous Pluto study with a mass of 10 kg was not a viable. option. Power is also a key limiting factor.

Indeed a low mass inertial reference unit implies that it will be below navigation grade. This means that the burden for attitude determination will be carried by the star tracker, which will have the capability of pointing anywhere in the unobstructed celestial sphere to aid in determining the 3-axis attitude of the spacecraft. in the next sections we will describe the key attitude determination hardware - the inertial reference unit and the star tracker.

INERTIAL REFERENCE UNIT

The inertial reference unit (IRU) on the Pluto spacecraft will be used to sense rates during trajectory correction maneuvers, following release of the spin-ejected drop probe, and during any anomalous spin modes. The IRU selected for the FY 94 baseline study was the Honeywell Lightweight Attitude Reference Unit which contains 3 Honeywell GG1308 ring laser gyros. The IRU has a mass of 210 grams and consumes 6.1 watts.

For purposes of (discussion in this paper, a gyro is defined as a device which measures angular change. or angular rate about one axis, an inertial reference unit contains two or more gyros and an inertial measurement unit is an IRU that also carries an accelerometer.

A Lightweight Attitude Reference Unit on loan from Lawrence Livermore National laboratory was tested at J]']. during, the latter half of 1993 as part of the Pluto Advanced Technology Insertion program.

The performance characteristic of most interest is the bias instability which has been measured around 1 deg/hour (1σ). Even better performance is expected in future devices and smaller bias instabilities have been measured on a number of ring laser gyros produced to date by Honeywell. The 1 deg/hour bias instability should be adequate for TCM control on the Pluto spacecraft.

Bias instability is not the only noise characteristic of interest in the IRU. Other noise sources include quantization noise, angle random walk, rate random walk and rate ramp. For the Honeywell ring laser gyro, a rate random walk noise component could not be detected. Note that rate ramp noise for the ring laser gyro is significant only for long integration times ($\tau > 10^5$ scuds). Angle random walk was measured at O.119 deg/$\sqrt{\text{hr}}$.

Based on these noise sources it was determined that the IRU could find spacecraft rate to within 312 μrad/sec at a 2.5 Hz update rate (400 msec integration). After a 100 second integration period, rates could be determined within 33 μrad/sec. Clearly the IRU was not going to be usable to control spacecraft rate to 10 μrad/sec.

STAR TRACKER

The key assembly in support of precision pointing by the attitude control subsystem is the star tracker. Recall that star sensors for three axis controlled spacecraft generally fall into one of three categories: a star camera, a star tracker or a stellar compass. The three devices are marked by increasing levels of internal processing. The star camera is simply a camera which sends out a stream of pixel information to be processed by a spacecraft on-board processor. A star tracker will send out centroid information on the objects in the field of view. The stellar compass has enough internal processing to calculate an attitude from the observed star field.

The 1 'Y 94 Pluto baseline considered a star [racker based on the Hughes Danbury Optical Systems (111)0S) HD-1003 star trackers. The Pluto star tracker is sometimes referred to as (he Planetary h4icro-Tracker. The modifications to the HD-1003 for usc in the 1 'Y 94 baseline include the. deletion of the power conditioning, unit, elimination of some radiation shielding and the use of a slower update rate (2.5 Hz vs. 10 Hz). in FY 94 HDOS completed a Planetary Micro-"1'racker hardware and software demonstration and assessment as one of many Advanced Technology 1 nsert ion efforts sponsored by the Pluto Preproject.

Tracker Characteristics

The mass of the tracker is 2 kg and it uses an average of" 2.7 watts, with 3.5 watts being the peak power consumed. The tracker can follow up to 6 stars at a time and has a sun exclusion angle of 45 degrees. The tracker is capable of being reprogrammed in flight. The star tracker make.s use of a 1 .oral Aeronutronic produced CCD and has an 8 degree x 8 degree field of view.

The end of life accuracy (angular accuracy) 01 the tracker for magnitude 6 stars (Mv = 6) is 17,7 μrad (1 σ) for 2 axis knowledge (1 star) and 255 μrad (1 σ) for 3 axis knowledge (2 stars).

Contributing to the tracker error budget arc boresight accuracy and accuracy with respect to the boresight. The boresight accuracy term will act as a constant or a bias and so will have no impact on the calculation of roll (twist about the tracker boresight) accuracy, nor will it contribute as a noise source when estimating the rate of spacecraft.

The elements contributing to the boresight error are: calibration knowledge, launch/mechanical hysteresis, temperature correction residual and charge transfer efficiency residual.

The accuracy with respect to the boresight (which does impact roll and rate calculations) includes these terms: calibration knowledge, low spatial frequency terms, centroiding errors and line of sight error for spacecraft motions up to 0.05 deg/sec.

The centroiding error term, which accounts for high spatial frequency errors in the sensing and data processing system, includes: sensor noise, sensor nonuniformity, sensor full wc]] capacity and nonlinearity thresholding effects, analog to digital quantization, quantization noise and nonuniformity, centroid spatial quantization, c. ffects of the grouping algorithm for illuminated pixels and charge transfer inefficiency and its uncertainty.

in addition, as part of the assessment task mentioned earlier, HDOS estimated the pointing accuracy for real star statistics in the vicinity of Pluto and assuming the tracker had been calibrated against an imaging instrument to take out the bias errors. In this case the pointing errors arc 5.8 μrad (1 σ) for pitch, 5.2 μrad (1 σ) for yaw and 105 μrad (1σ) for yaw.

The vendor also demonstrated the ability to use the centroiding algorithms of the device to [rack the limb of a planetary body like Pluto or Charon.

PRECISION POINTING

The biggest precision pointing challenge for the Pluto spacecraft is tbc maintenance of the desired image motion compensation rate to within 10 μrad/sec. Meeting the 2 mrad control accuracy requirement will not be difficult, so we will focus on the 10 μrad/sec rate control issue.

As was mentioned earlier, the inertial reference unit will not be of usc for precision pointing during Pluto science imaging, be.cause of its low accuracy. So the burden of attitude determination is carried by the star tracker during this critical period, with the cold gas thrusters providing the attitude control.

Because of the noisiness of the star tracker, closed loop control dots not look attractive for rate control during flyby science imaging. Instead open loop schemes arc being investigated for pointing control during the flybys. This is reminiscent of the very successful "nodding image motion compensation" schemes used by Voyager 2 during its flybys of Neptune and Triton in August of 1989. In this scheme the spacecraft would command its thrusters in a preplanned (i.e. open loop) thrust profile to turn the camera to a target, take onc or two images at the proper image motion compensation rate and then turn back to Earth to transmit the data. Note that the scan platform was not used in this scenario.

The scheme for the Pluto spacecraft will be to execute the imaging mosaics for the mission in an open-loop manner while pausing at appropriate intervals to check the pointing and rate accuracy and to make adjustments as needed. All images will be stored for relay to Earth following the encounter.

One of the key concerns in implementing this strategy is the amount of time. that is required to calculate the rate of the spacecraft to the desired accuracy using the star tracker data. A least squares analysis was done to determine the uncertainty in rate knowledge onc would achieve after taking, star measurements over a period of time. The result is:

$$\sigma_{\omega} = \sigma_{tr}\, r\, [12/(m^3 - m)]^{0.5} \qquad (1)$$

In Eq. (1) σ_{ω} is the uncertainty in estimated spacecraft rate, σ_{tr} is the star tracker accuracy for the axis of concern, r is the update rate of the tracker (2.5 Hz), **and m** is the number of star field images processed over a period of time. (If we were taking data for only **4** seconds, then m = 10, with an update rate of r = 2.5 Hz.)

The above analysis assumes that there are no external disturbances acting on the spacecraft during the time that the rate is being estimate.d. Based on the Voyager 2 experience and the present design of the Pluto spacecraft, this appears to be a reasonable assumption.

In our analysis we will not use that portion of the star tracker error which is considered a bias, as the bias will have no impact on calculating the rate as we average over several tracker frames.

The star tracker will be boresighted 60 degrees around the circumference of the bus from the science imager, and so a transformation needs be made from the angular errors at the tracker boresight to the boresight of the science imager. This transformation will take into account, for example, the large tracker roll error will have on pointing in non-roll directions on the science imager boresight.

in addition, if it were possible to have two star trackers on simultaneously and the two tracker boresights were 90 degrees apart, then we would have three axis attitude determination accuracy equal to that of the pitch and yaw accuracies of the tracker. The second tracker allows a dramatic improvement in what had been the poorer accuracy for the roll axis with just one tracker.

Using Eq. (1) and the assumptions stated above, we present in Table 1 the time required to determine spacecraft rate to the desired accuracy.

Table 1
TIME IN SECONDS REQUIRED TO DETERMINE SPACECRAFT RATE WITHIN 10 μrad/s (3 σ)

Tracker Status	Mv = 6 stars	Pluto typical stars
1 tracker on	29	15.4
2 trackers on	2,4	1.6

If the attitude rate estimator had apriori information that the rate was already within say 50 μrad/sec of the desired rate, that information could be used to reduce the amount of estimation time listed in Table 1 above.

Prior to the Pluto encounter the rates imparted by the thruster impulses will be calibrated. But despite the calibration, the uncertainty from impulse to impulse will have to be taken into account. We now map thruster impulse uncertainties into rate errors following a slew. In the analysis the uncertainty in spacecraft rate as a function of impulse bit uncertainty was modeled as:

$$\sigma_\omega = \sigma_p [(4\, d\, F\, \Delta\Theta)/I]^{0.5} \qquad (2)$$

where σ_p is the 1 σ nondimensional uncertainty in impulse bit, d is the moment arm in meters, F is the thrust in Newtons, $\Delta\Theta$ is the slew angle in radians, and I is the applicable moment of inertia in kg-m^2. A moment of inertia of 15 kg-m^2 is used in this case.

Also note that after n separate slews where there is no correction for rate errors after each slew and the random effects of each slew arc considered independent, then the , uncertainty in rate, $\sigma_{\omega n}$, will be

$$\sigma_{\omega n} = \sqrt{n}\,\sigma_{\omega} \tag{3}$$

The above equations tell us that thruster repeatability errors need to be less than 0.25% ($3\sigma_p$ = 0.0025) in order to allow a 6 frame sequence to proceed open loop and still have the rate within 10 μrad/s at the final frame. ('This assumes 5 step sizes each of 8 mr). For one 8 mr step size the repeatability of impulse. bits would only need to be about 0.6% to ensure the rate would be within 10 μrad/s of the. desired rate. Note that for a 1% repeatability error for the impulse bit, the uncertainty in rate after an 8 mr step is 16.6 μrad/s.

The amount of repeatability error that could be expected for the impulse bit of a 0.005 N cold gas thruster is being investigated by the Propulsion subsystem and will be of great use in determining how frequently the controller will have to pause and reestimate the rate of the spacecraft during a science mosaic.

Despite the fact that the analysis is very basic at this point, open loop control during science taking with appropriate pauses to check and adjust the rate appears feasible. The drawback of this scheme is the large amount of time that may have to be expended to estimate rates and then make a rate adjustment if necessary. If the time expenditure is found to negatively impact the science needed to minimally justify a Pluto mission, then a new pointing scheme will have to be found. The use of a fast steering mirror in the science imager itself could be one option to explore in that case.

CONCLUSION

A cost, mass and schedule constrained mission to Pluto will naturally impact the pointing performance that can be expected during a fast flyby. In this paper we have focused on some precision pointing concepts that could work within the constraints of the Pluto mission.

These constraints require a moderate performance inertial reference unit that will be used to control trajectory correction maneuver pointing, but will not be of sufficient precision to assist in science imaging. Therefore, the burden of attitude determination during the Pluto encounter will fall on the star tracker. Control of the three axis spacecraft will be executed by miniature cold gas thrusters.

The paper focused on the most demanding of the pointing requirements, which prescribes the spacecraft rate be controlled within 10 μrad/sec. Closed loop control appears problematic for rate control of this precision because of the star tracker noise. An open loop scheme was suggested as a means of executing the imaging sequence while monitoring and maintaining the desired spacecraft rate.

The entire attitude control subsystem design will continue to be evaluated against the requirements and constraints as the mission design evolves. For the precision pointing issue, work will likely focus on adaptive estimation schemes and nonlinear control methods in order to maximize the performance of the given hardware.

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